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16. Abstract

Ultrashort-wave propagation in the Venusian atmosphere is investigated in two models as a function of the vertical distribution of the electromagnetic refractive index. The Venusian atmosphere is found to be turbulent to an altitude of about 40 km, radio wave attenuation in the Venusian atmosphere is caused mainly by molecular absorption, and refractive effects are strong in the atmosphere of Venus.

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# ANALYSIS OF RADIO WAVE PROPAGATION IN THE VENUSIAN ATMOSPHERE

O. I. Yakovlev

Ultrashort-wave propagation in the atmosphere of Venus depends strongly on /372* the altitude distribution of the electromagnetic refractive index n(h), which is determined by the gas composition, pressure P and temperature T. On the basis of [1] the following gas composition is used: 95% $CO_2$ and 5% $N_2$. The refractive index of gas of the stated composition is expressed by relations of the form:

$$n(h)=1+N(h);\qquad N(h)=0.13P(h)\cdot T^{-1}(h) \tag{1}$$

Here P is expressed in atmospheres, T in degrees Kelvin. The functions P(h) and T(h) are presented in [2, 8], but their surface values are approximate. To determine the function N(h) we will examine two models of the Venusian atmosphere. The first model is characterized by surface pressure $P_0$ = 92 atm, the second model by $P_0$ = 63 atm.

Analysis of the functions P(h) and T(h) in [2, 8] yielded the following dependence of the function N(h):

$$N(h)=\exp(-ah^2-bh-c). \tag{2}$$

Here a = $5.79\cdot10^{-4}$ $km^{-2}$, b = $4.4\cdot10^{-2}$ $km^{-1}$, c = 4.11. These parameters correspond to the conventional zero altitude with pressure $P_0$ = 92 atm. The second model of the Venusian atmosphere with pressure $P_0$ = 63 atm corresponds also to approximation (2), but with the displacement of altitude h* = h - 6 km. The profile of N(h) can be used for analyzing the refractive effects in the Venusian atmosphere.

Analysis of the refractive effects amounts to determination of the angles of refraction, refraction attenuation and conditions of capture of electromagnetic radiation by the Venusian atmosphere. Refractive effects are strong in the Venusian atmosphere. Thus, for ray elevation angle θ less than the critical angle $\theta_{cr}$, the ray does not escape from the atmosphere. For the first model of the atmosphere $\theta_{cr}$ = 7.6°, and for the second $\theta_{cr}$ = 6°. For $\theta = \theta_{cr}$

*Numbers in the margin indicate pagination in the foreign text.

the ray is captured at the critical refraction altitude, corresponding to a pressure of about 7 atm. For ray elevation angle $\theta > \theta_{cr}$ the rays escape from the atmosphere of the planet, distorted by refraction angle $\xi$, determined by the known refraction integral. Since the refraction angle depends to a great extent on elevation, refraction attenuation of electromagnetic radiation is pronounced in the Venusian atmosphere. Refraction attenuation of electromagnetic radiation is expressed by the relation $S = S_0(1 + |d\xi/d\theta|)^{-1}$. The angle of refraction $\xi$ and refraction attenuation $S/S_0$ are presented in Figures 1 and 2 as functions of elevation. /373

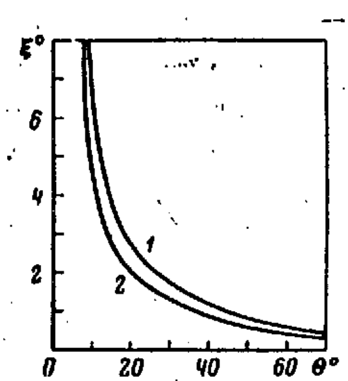


Figure 1. Angle of Refraction $\xi$ as Function of Ray Elevation $\theta$: 1, for $P_0$ = 92 atm; 2, for $P_0$ = 63 atm.

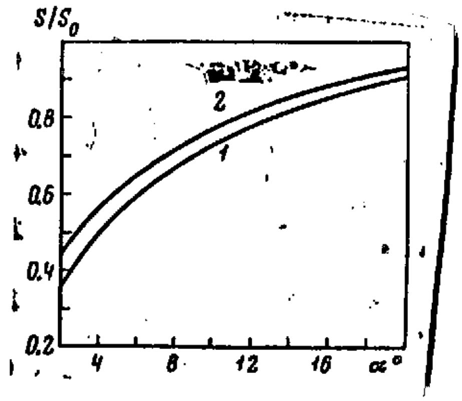


Figure 2. Refraction Attenuation of Electromagnetic Radiation $S/S_0$ as Function of True Angle of Elevation to Earth $\alpha = \theta - \xi$: 1, for $P_0$ = 92 atm; 2, for $P_0$ = 63 atm.

Electromagnetic propagation in the Venusian atmosphere was investigated directly from the Venus-4 space probe in the $\lambda$ = 30 cm band [5]. It was found as a result of this experiment that when the transmitter is located at the level corresponding to pressure P = 18 atm there is practically no attenuation of decimeter waves. When the Venus-4 probe entered the troposphere of Venus it detected rapid fluctuations of field intensity with a characteristic period of the order of 0.7 s. The observed dependence of the magnitude of the rapid fluctuations of $\eta$ on the altitude of the probe is depicted in Figure 3. The altitude h = 0 corresponds in Figure 2 to pressure P = 18 atm, where $\eta$ = = 5-10%. Analysis of the fluctuations of the radio waves indicates that the Venusian troposphere is inhomogeneous to altitudes of the order of 40 km.

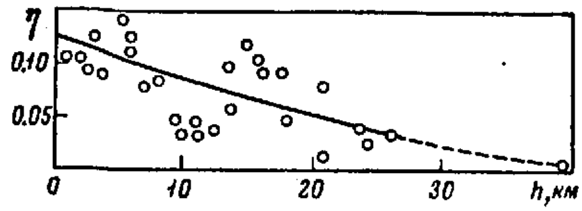


Figure 3. Rapid Fluctuations of Radio Signals of "Venera-4" Probe as Function of Altitude.

Fluctuations of the refractive index, which cause rapid fluctuations of radio waves, $\Delta N_{av} \approx 10^{-5}$, is an order of magnitude greater than the values characteristic of the geotroposphere. The fluctuations of the radio waves indicate turbulent mixing of the Venusian troposphere.

Absorption of the energy of electromagnetic radiation is described by the relation

$$S = S_0 \exp\left(-\frac{\Delta}{\lambda^2 \sin\theta}\right). \tag{3}$$

This relation is valid for $\theta > 10°$. The parameter $\Delta$, according to [7], is expressed through P and T:

$$\Delta = L \cdot \left[\int_0^\infty P^2(h) \cdot T^{-5}(h)\, dh\right] \cdot 10^{-8}\ cм^{+2}. \tag{4}$$

Here L is a numerical coefficient, which depends on the gas composition of the atmosphere. For 95% $CO_2$, 5% $N_2$ and 0.1% $H_2O$ [7], L = 14.3. Analysis revealed that the following approximation is suitable:

$$P^2 \cdot T^{-5} = \exp(-Ah^2 - Bh + C), \tag{5}$$

where $A = 8.36 \cdot 10^{-4}$ km$^{-2}$, $B = 5.67 \cdot 10^{-2}$ km$^{-1}$, C = 4.03. Approximation (5) for h = 0 corresponds to $P_0$ = 92 atm, and the model with $P_0$ = 63 atm is described by (5) after substitution of $h^* = h - 6$ km. From (4) and (5) we have

$$\Delta = L \sqrt{\frac{\pi}{A}} \cdot \left[\frac{1}{2} - \Phi\right] \cdot \exp\left(\frac{B^2}{4A} - C\right) \cdot 10^{-8}\ cм^{+2}. \tag{6}$$

Here $\Phi(B/\sqrt{2A})$ is the tabulated probability integral. The parameter $\Delta$, computed according to (6) for various pressures, is presented in the table.

Changes of the radar cross section $\sigma$ of Venus also makes it possible to estimate the parameter $\Delta$. These estimates depend on the assumed frequency dependence of the dielectric constant of surface rocks of the planet $\varepsilon$.

Assuming that $\varepsilon$ does not depend on wavelength, we obtain the maximum estimate of $\Delta$. If we assume that for $\lambda > 40$ cm $\varepsilon = 4.8$, and for $\lambda = 3.8$ cm $\varepsilon = 3.4$, then we obtain the minimum estimate of the parameter $\Delta$. The values $\Delta_{min}$ and /374
$\Delta_{max}$, determined on the basis of radar data, are presented in the table. The probable value is $\Delta = (12 \pm 2)$ cm$^2$, which corresponds to surface pressures $P_0 = 80$-$120$ atm. The presence of inhomogeneities of refraction indicates possible scattering of radio waves. Attenuation due to scattering is also described by an expression of the form (3), but here parameter $\Delta^*$ has a different meaning. $\Delta^* \approx \Delta w^2_{av}$ Hb, where H is the thickness of the turbulent region and b is the conventional scale of inhomogeneities [4]. According to estimates $\Delta^* = (2$-$4)$ cm$^2$. Figure 4 depicts attenuation during one-time passage of radio waves as a function of wavelength for two angles of elevation; refraction attenuation of electromagnetic radiation for the first model of the atmosphere is taken into consideration for the small elevation angle.

VALUES OF $\Delta$ (MEASURED IN cm$^2$)

| $P_0$, atm | 71 | 92 | 103 | 114 | Radar | |
|---|---|---|---|---|---|---|
| | | | | | minimum | maximum |
| $\Delta$, cm$^2$ | 7,77 | 10,6 | 12,0 | 14,3 | 10 | 14 |

Note: Commas indicate decimal points.

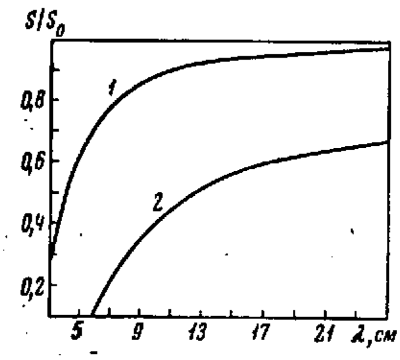


Figure 4. Attenuation of Energy of Electromagnetic Radiation as Function of Wavelengths: 1, for $\alpha = 90°$; 2, for $\alpha = 12°$.
Note: Commas indicate decimal points.

## Conclusions

1. The Venusian atmosphere is turbulent to an altitude of the order of 40 km. Fluctuations of the refractive index of electromagnetic radiation are an order of magnitude greater than the fluctuations that are characteristic of the troposphere of the earth. The presence of these inhomogeneities leads to fluctuations, and perhaps scattering of radio waves.

2. Attenuation of radio waves in the Venusian atmosphere is caused basically by molecular absorption. At small elevation angles there is also refraction attenuation of radio waves. If the contribution of scattering to the total attenuation is ignored, the surface pressure should be $P_0$ = 80-120 atm. Consideration of scattering in the estimation of absorption yields $P_0$ = = 60-80 atm.

3. Refractive effects are strong in the atmosphere of the planet. At elevation angles less than 6-7° radio waves are captured and the ray line does not extend beyond the atmosphere of Venus. Critical refraction takes place in the region corresponding to P = 7 atm.

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